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**Market Manual 3: Metering**  
**Part 3.5: Site-Specific**  
**Loss Adjustments**

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**Issue 7.0**

This document provides guidance to *metering service providers* on how to calculate and submit Site-Specific Loss Adjustments (SSLA) to the *IMO*.

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|                         |  |
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# Table of Changes

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| <b>Reference:</b>   | <b>Description of Change</b>   |
|---------------------|--|
| Throughout document | Replaced IMO with <i>IESO</i> .  |
| Section 2           | Replaced IMO with <i>IESO</i> in Figure 2.1 in the heading and box 3.04. |

# Market Manuals

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The *market manuals* consolidate external procedures and associated forms, standards, and policies that define specific elements relating to the operation of the *IESO-administered markets*. External procedures are guides for the use of *market participants* that provide a more detailed description of the requirements for various activities than is specified in the “*Market Rules*”. Standards and policies provide a supporting framework for the external procedures. Where there is a discrepancy between the requirements in a document within a *market manual* and the “*Market Rules*”, the “*Market Rules*” shall prevail. (Chapter 1, Section 7.6A.1)

## Market Procedures

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This document is Volume 3.5 of the *market manuals*, where:

- “Market Manual 3” is the “Metering Manual”, and
- Part 5 describes the “Site Specific Loss Adjustments (SSLA)” procedure.

A list of the other component parts of the “Metering Manual” is provided in “Part 3.0: Metering Overview”.

## Structure of Market Procedures

Each market procedure is composed of the following sections:

1. “**Introduction**”, which contains general information about the procedure, including an overview, a description of the purpose and scope of the procedure, and information about roles and responsibilities of the parties involved in the procedure.
2. “**Procedural Work Flow**”, which contains a graphical representation of the steps and flow of information within the procedure.
3. “**Procedural Steps**”, which contains a table that describes each step and provides other details related to each step.
4. “**Appendices**”, which may include such items as forms, standards, policies, and agreements.

## Conventions

The *market manual* standard conventions are defined in the “Market Manual Overview” document.

– End of Section –



# 1. Introduction

---

## 1.1 Purpose

This procedure describes how to calculate and submit Site-Specific Loss Adjustments (SSLA) to the *IESO*.

## 1.2 Scope

This procedure is intended to provide *market participants* with a summary of the steps and interfaces between *market participants*, the *IESO* and other parties for performing site-specific loss adjustment. The procedural steps and work flows described in this document serve as a roadmap for *market participants* and the *IESO*, and should be used in conjunction with the "*Market Rules*". The overview information in Section 1.3, below, which is provided for convenience of reference only, highlights the main actions that comprise the procedure as described in greater detail in later sections of this document. For further information see "IESO Standard Site Specific Loss Adjustments – Requirements for Adjustment of Meter Readings for Site-Specific Losses in the IESO-Administered Market (SSLA standard)".

Site-specific loss adjustments apply to *metering service providers* (MSPs) and all *metering installations* in the *IESO-administered markets*.

Loss adjustments are required for:

- radial line loss (voltage-dependent loss and current-dependent loss); and
- transformer loss (voltage-dependent power loss and current-dependent power loss).

## 1.3 Overview

The "*Market Rules*" include requirements that are designed to ensure the equitable treatment of all *metered market participants* (MMPs) in terms of measurement in the context of the *IESO-administered markets*. To promote maximum measurement accuracy, the *meter point* of a wholesale *meter* is required to be located as close as possible to the *defined meter point* for each *connection point*. (Chapter 6, Section 4.2.1.1) When this is not the case, data obtained from the *metering installation* requires site-specific loss adjustment (SSLA). (Chapter 6, Section 4.2.3) The adjusted readings reflect the readings that would have been obtained if the metering were installed at the *defined meter point*. (Chapter 6, Section 4.2.4)

Site-specific loss adjustments are calculated for both power transformers and radial transmission lines. The *IESO* provides separate loss models for lines and transformers, respectively.

At the time that the *meter point* associated with a *metering installation* is registered, the *metering service provider* must submit SSLA coefficients to the *IESO* using the SSLA register available on the *IESO's* Web site. See also "Market Manual 3: Metering, Part 3.2: Meter Point Registration and Maintenance". When loss adjustments are required to be provided to the *IESO*, the *metering service provider* must also ensure that the SSLA register containing the final loss adjustment coefficients is stamped and signed by a registered professional engineer. Site-specific loss adjustments are then re-submitted by the *metering service provider* during the submission of totalization tables. For details, see Market Manual 3: Metering Part 3.7: Totalization Table Registration.

Examples of the manner in which loss coefficients may be calculated are set forth in Appendix B. Additional calculation examples and supplementary information may be found in the SSLA Standard. Additional SSLA-relevant information may also be found in the "IESO Standard Wholesale Revenue Metering Standard-Hardware". Additional information of loss calculation for the settlement system can be found in the MV-STAR Reference Guide – Loss Equations.

At the present time, the settlement system will only adjust losses for Active Energy (kWh). MSPs must submit an SSLA register that contains coefficients for all applicable kWh related loss components (A,B,E,F,K1,K2,K3). At the present time the IESO will accept SSLA registers that do not include kVARh related coefficients (C,D,G,H,K4,K5,K6). However, when the settlement system is modified to adjust losses for Reactive Energy (kVARh), the active MSP responsible for a metering installation for which the SSLA register on file with the IESO does not contain kVARh related coefficients (C,D,G,H,K4,K5,K6) will be required to submit a revised SSLA register including these coefficients.

## 1.4 Roles and Responsibilities

Responsibility for carrying out site-specific loss adjustments is shared among:

- *Metering service providers*, which are responsible for:
  - providing valid and accurate SSLA coefficients for radial line loss (voltage-dependent loss and current-dependent loss);
  - providing valid and accurate SSLA coefficients for transformer loss (voltage-dependent power loss and current-dependent power loss);
  - ensuring that a registered professional engineer stamps and signs the SSLA Register;
  - submitting SSLA information to the *IESO* at the time of *meter point* registration; and
  - re-submitting SSLA when necessary by following the relevant change process described in "Market Manual 3: Metering, Part 3.2: Metering Point Registration.
- The *IESO*, which is responsible for:
  - defining loss adjustment models and submission format; and
  - receiving and reviewing SSLA loss adjustment coefficients.

## 1.5 Contact Information

If the *market participant* wishes to contact the *IESO*, the *market participant* can contact the *IESO* Help Centre via email at [customer.relations@ieso.ca](mailto:customer.relations@ieso.ca) or via telephone, mail or courier to the numbers and addresses given on the *IESO*'s Web site ([www.ieso.ca](http://www.ieso.ca) – or click on 'Have a question?' to go to the 'Contacting the IESO' page). If the *IESO* Help Centre is closed, telephone messages or emails may be left in relevant voice or electronic *IESO* mail boxes, which will be answered as soon as possible by Help Centre staff.

Standard forms that participants must complete for this procedure are listed in Appendix A. These forms are generally available for downloading on the *IESO*'s public Web site. These signed forms as well as the accompanying supporting documentation must be transmitted to the *IESO* via mail or courier by using the appropriate address provided on the *IESO*'s public Web site or on the form. All correspondence relating to this procedure shall identify the subject: **Site-Specific Loss Adjustments**.

– End of Section –

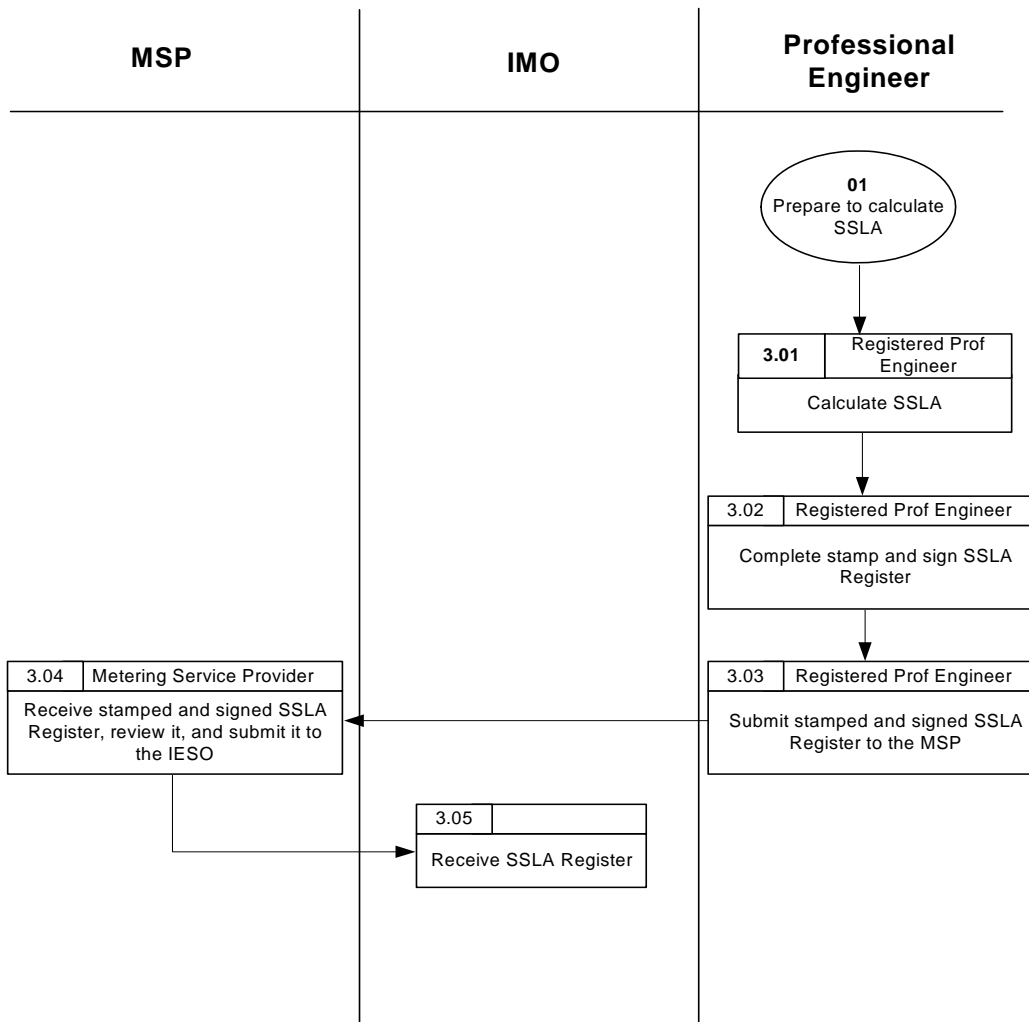
## 2. Procedural Work Flow

The following diagram represents the flow of work and information related to Site-Specific Loss Adjustments (SSLA) among the *IESO*, the *metering service provider* and the Registered Professional Engineer.

The steps illustrated in the diagram are described in detail in Section 3.

**Table 2–1: Legend for Procedural Work Flow Diagrams**

| <b>Legend</b>         | <b>Description</b>  |
|-----------------------|---|
| Oval                  | An event that triggers task or that completes task. Trigger events and completion events are numbered sequentially within procedure (01 to 99).   |
| Task Box              | Shows reference number, party responsible for performing task (if “other party”), and task name or brief summary of task. Reference number (e.g., 1A.02) indicates procedure number within current <i>market manual</i> (1), subprocedure identifier (if applicable) (A), and task number (02). |
| Solid horizontal line | Shows information flow between the <i>IESO</i> and external parties.  |
| Solid vertical line   | Shows linkage between tasks.  |
| Broken line           | Links trigger events and completion events to preceding or succeeding task.   |



**Figure 2–1: Procedural Work Flow for Site-Specific Loss Adjustments (SSLA)**

– End of Section –

## 3. Procedural Steps

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This section contains detail on the tasks (steps) that comprise the Site-Specific Loss Adjustments procedure.

The table contains seven columns, as follows:

### **Ref**

The numerical reference to the task.

### **Task Name**

The task name as identified in Section 2.

### **Task Detail**

Detail about the task.

### **When**

A list of the information flows that may or must result from the task.

### **Method**

The format and method for each information flow are specified.

### **Completion Events**

A list of all the circumstances in which the task should be deemed finished.

The steps in the following table are illustrated in Section 2:

**Table 3–1: Procedural Steps for Site-Specific Loss Adjustments**

| <b>Ref.</b> | <b>Task Name</b>  | <b>Task Detail</b>  | <b>When</b>                     | <b>Resulting Information</b>              | <b>Method</b> | <b>Completion Events</b>    |
|-------------|---|---|---------------------------------|---|---------------|-----------------------------|
| 01          | Prepare to calculate SSLA   | Registered Professional Engineer determines whether Method 1 or Method 2 calculation applies as described in the SSLA Register.   | Initial step                    |   |               |                             |
| 3.01        | Calculate SSLA  | Registered Professional Engineer calculates SSLA according to requirements of the “ <i>Market Rules</i> ” (Chapter 6-Appendices, Appendix 6.5, section 1.3.3) and of any policy or standard established by the <i>IESO</i> based on power transformer, radial line, <i>revenue meter</i> and <i>instrument transformer</i> data.<br><br>Registered Professional Engineer calculates loss coefficients using Method 1 or Method 2. |                                 | Completed SSLA as required by <i>IESO</i> |               | SSLA calculations completed |
| 3.02        | Complete, stamp, and sign SSLA Register   | Registered Professional Engineer completes and signs SSLA Register and applies Professional Engineer Ontario (PEO) stamp.   | After calculations are complete | Certified SSLA                            |               | Certified SSLA              |
| 3.03        | Submit stamped and signed SSLA Register to <i>metering service provider</i> (MSP) | Engineer submits stamped and signed SSLA Register to <i>metering service provider</i> for review.   | After calculations are complete |   | Fax or e-mail |                             |

| <b>Ref.</b> | <b>Task Name</b>  | <b>Task Detail</b>   | <b>When</b>   | <b>Resulting Information</b>                                  | <b>Method</b>                                      | <b>Completion Events</b> |
|-------------|---|--|---|---|--|--------------------------|
| 3.04        | Receive SSLA Register, review it and submit it to the IESO. | <i>Metering service provider</i> receives and reviews stamped and signed SSLA Register.<br><i>Metering service provider</i> submits stamped and signed SSLA Register, together with other Metering Installation Registration (MIR) documents, to the IESO. | After <i>metering service provider</i> receives stamped and signed SSLA Register. | As per <i>metering installation</i> registration requirements | Fax or e-mail; original to follow by regular mail. |                          |
| 3.05        | Receive SSLA Register                                       | Receive stamped and signed SSLA Register.  | After <i>metering service provider</i> submits SSLA                               |   |  |                          |

– End of Section –





## Appendix A: Forms

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This appendix contains a list of the forms and letters associated with the SSLA procedure, which are available on the *IESO's* public Web site (<http://www.ieso.ca>). The forms and letters included are as follows:

| <b>Form Name</b>                       | <b>Form Number</b> |
|--|--------------------|
| Site-Specific Loss Adjustment Register | IMO-FORM-1040      |
| Totalization Table Form                | IMO-FORM-1310      |

– End of Section –



# Appendix B: Method 1 - Volt Squared and Amp Squared Coefficients (A,B,C,D)

## B.1 Introduction

The "Market Rules" permit a *metering installation* to be registered notwithstanding that the *meter point* is not located at the *defined meter point*, if appropriate site-specific loss adjustment parameters are provided at the time of registration. (Chapter 6, Section 4.2.4) This may mean adjusting for losses in a radial line or in a power transformer.

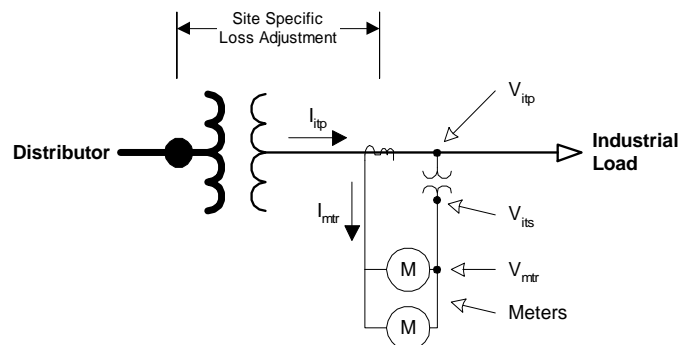
This appendix provides additional examples showing how loss coefficients can be developed for power transformers in compliance with the SSLA Standard posted at [www.ieso.ca](http://www.ieso.ca).

In most cases, factory test results for impedance and load loss are available and loss calculations are based on these test results. In cases where the factory test results have been lost, the SSLA Standard requires the use of default transformer parameters. Use of default assumptions is illustrated below.

All *metering installations* that comply with the IESO requirements will record volt squared and ampere squared hours per element. Use of these figures achieves the best accuracy. For *metering installations* that are permitted to be registered even if they do not record volt squared, amp squared or var hours, the use of standard loss coefficients is also possible. The calculation of such coefficients is illustrated below.

## B.2 Fixed Tap Power Transformer on Rated Tap

The figure below illustrates a typical situation requiring site specific loss adjustments for active and reactive power.



**Figure B-1: Metering Installation for which Site Specific Loss Adjustments are Calculated**

In this example, the *metering installation* has been installed on the secondary side of the power transformer but the *defined meter point* is on the high voltage side. The power transformer is a 1000 kVA, 44kV/600V, delta-wye grounded. The transformer does not have an under load tap changer but the high voltage winding has fixed taps at 44.0, 41.8, 42.9, 45.1 and 46.2 kV. The transformer is operating on the 44.0 kV tap, which is the nominal, or principal tap.

$$CT_{\text{ratio}} = \frac{1000 \text{ A}}{5 \text{ A}} \quad \text{Line Current}$$

$$VT_{\text{ratio}} = \frac{360 \text{ V}}{120 \text{ V}} \quad \text{Phase - Neutral}$$

### Meter = Three Element

**Figure B-2: Metering Data for the Metering Installation shown in Figure B-1**

The factory test results for transformer 1

|  |                 |
|--|-----------------|
| $S_{\text{rated}} = 1000 \text{ kVA}$        | Three phase     |
| $V_{\text{rated}} = 600 \text{ V}$           | Line - Line     |
| $P_{\text{no load loss}} = 3.585 \text{ kW}$ | Loss at no load |
| $I_{\text{ex}} = 1.93 \%$                    | Exiting Current |
| $P_{\text{load loss}} = 9.693 \text{ kW}$    | Load Loss       |
| $Z = 5.72 \%$                                | Impedance       |

**Figure B-3: Factory Test Results for Transformer 1**

## Calculation of Transformer 1 Losses from Factory Test Results

$$V_{itp} = V_{rated} \div \sqrt{3} \quad V_{itp} = 346.41 \text{ V} \quad L - N$$

$$I_{itp} = S_{rated} \div (\sqrt{3} \times V_{rated}) \quad I_{itp} = 962.25 \text{ A} \quad \text{Three phase}$$

$$Q_{noloadLoss} = \sqrt{(I_{ex} \times S_{rated})^2 - P_{noloadLoss}^2} \quad Q_{noloadLoss} = 18.964 \text{ kVAR} \quad \text{Three phase}$$

$$Q_{loadLoss} = \sqrt{(Z \times S_{rated})^2 - P_{loadLoss}^2} \quad Q_{loadLoss} = 56.373 \text{ kVAR} \quad \text{Three phase}$$

**Figure B-4: Calculation of Transformer 1 Losses**

## Calculation of Loss Coefficients for Transformer 1

$$A = \frac{P_{noloadLoss}}{3} \div \left( \frac{V_{itp}}{V_{T_{ratio}}} \right)^2 \quad A = 89.625 \times 10^{-6} \frac{\text{kW}}{\text{V}^2} \quad \text{Per Phase}$$

$$B = \frac{P_{loadLoss}}{3} \div \left( \frac{I_{itp}}{CT_{ratio}} \right)^2 \quad B = 139.579 \times 10^{-3} \frac{\text{kW}}{\text{amp}^2} \quad \text{Per Phase}$$

$$C = \frac{Q_{noloadLoss}}{3} \div \left( \frac{V_{itp}}{V_{T_{ratio}}} \right)^4 \quad C = 35.557 \times 10^{-9} \frac{\text{kVAR}}{\text{V}^4} \quad \text{Per Phase}$$

$$D = \frac{Q_{loadLoss}}{3} \div \left( \frac{I_{itp}}{CT_{ratio}} \right)^2 \quad D = 811.767 \times 10^{-3} \frac{\text{kVAR}}{\text{amp}^2} \quad \text{Per Phase}$$

**Figure B-5: Calculation of Loss Coefficients for Transformer 1**

NOTE: Non-Blondel *metering installations* waived into the *IESO-administered Markets* after seal-expiry may use a 2 ½ element *meter* provided that: the compliant Main *meter* can 1) calculate the missing voltage and 2) record the volt square hour (missing voltage) in channel 6 for each interval.

### B.3 Delta Connected Metering Installations

This example shows how to calculate loss coefficients for two-element *metering installations*. For this example, it is assumed that the transformer has a delta-connected secondary and that a two-element *meter* is used to measure the power flow on the secondary.

$$CT_{\text{ratio}} = \frac{1000 \text{ A}}{5 \text{ A}}$$

$$VT_{\text{ratio}} = \frac{600 \text{ V}}{120 \text{ V}}$$

Meter = Two Element

### Figure B-6: Metering Data

The factory test results are as shown in Figure B-3. The transformer losses are calculated as shown in Figure B-4. The loss coefficients, however, are not the same as for three element metering. Their calculation is shown below.

|   |   |           |
|---|---|-----------|
| $A = \frac{P_{\text{noLoadLoss}}}{2} \div \left( \frac{V_{\text{ip}}}{VT_{\text{ratio}}} \right)^2$ | $A = 134.437 \times 10^{-6} \frac{\text{kW}}{\text{V}^2}$   | Per Phase |
| $B = \frac{P_{\text{loadLoss}}}{2} \div \left( \frac{I_{\text{ip}}}{CT_{\text{ratio}}} \right)^2$   | $B = 209.369 \times 10^{-3} \frac{\text{kW}}{\text{amp}^2}$ | Per Phase |
| $C = \frac{Q_{\text{noLoadLoss}}}{2} \div \left( \frac{V_{\text{ip}}}{VT_{\text{ratio}}} \right)^4$ | $C = 53.336 \times 10^{-9} \frac{\text{kVAR}}{\text{V}^4}$  | Per Phase |
| $D = \frac{Q_{\text{loadLoss}}}{2} \div \left( \frac{I_{\text{ip}}}{CT_{\text{ratio}}} \right)^2$   | $D = 1.218 \frac{\text{kVAR}}{\text{amp}^2}$                | Per Phase |

**Figure B-7: Calculation of Loss Coefficients for Two Element Metering**

## B.4 Power Transformer Off Principal Tap

System voltage conditions often require that transformers be placed into service on a tap other than the principal or nominal tap. Since CSA and ANSI require factory testing at the principal and at the extreme taps only, the factory test results may not have the loss figures for every tap. This example shows how to apply linear interpolation when the power transformer is not on the principal tap.

In this example, the factory test data refers to an 18 MVA, 130/4.16 kV power transformer. The transformer has five primary taps,  $\pm 10\%$  in 5% steps. The transformer is in service on tap 2. The secondary taps are fixed. The factory test results are shown below.

| No Load Loss |          |              |           |                     |
|--------------|----------|--------------|-----------|---------------------|
| Tap          | Test % V | Voltage (kV) | Loss (kW) | I <sub>ex</sub> (%) |
| 3            | 100      | 230          | 16.620    | 0.225               |

| Load Loss at 18 MVA |         |             |              |           |               |
|---------------------|---------|-------------|--------------|-----------|---------------|
| Tap                 | Winding | Rating (kV) | Rating (Amp) | Loss (kW) | Impedance (%) |
| 1                   | H-X     | 143.00      | 73           | 63.909    | 9.190         |
| 3                   | H-X     | 130.00      | 80           | 67.490    | 9.320         |
| 5                   | H-X     | 117.00      | 89           | 75.521    | 9.750         |

**Figure B-8: Factory Test Results For the 18 MVA Transformer**

Linear interpolation is required to determine the load loss and percentage impedance on tap 2.

S<sub>rated</sub> = 18 MVA                      Three phase  
 V<sub>rated</sub> = 4.160 kV                    Line-Line on secondary  
 P<sub>noLoadLoss</sub> = 16.62 kW            Loss at no load  
 I<sub>ex</sub> = 0.225%                        Exiting Current

Linear Interpolation for Off Nominal Tap

Load Loss:

$$P_{loadLoss} = 67.49 \cdot kW + \left( \frac{63.909 \cdot kW - 67.490 \cdot kW}{1 - 3} \right) (2 - 3) \quad P_{loadLoss} = 65.7 \cdot kW$$

Impedance:

$$Z = 9.32 \cdot \% + \left( \frac{9.19 \cdot \% - 9.32 \cdot \%}{1 - 3} \right) (2 - 3) \quad Z = 9.255 \%$$

**Figure B-9: Factory Test Data for the 18 MVA Power Transformer**

Three-element metering is installed on the secondary side of the power transformer.

The loss coefficients are as follows:



## Base Quantities

|  |   |             |
|--|---|-------------|
| $V_{itp} = V_{rated} \div \sqrt{3}$                                      | $V_{itp} = 2401.78 \text{ V}$                   | L-N         |
| $I_{itp} = S_{rated} \div (\sqrt{3} \times V_{rated})$                   | $I_{itp} = 2498.15 \text{ A}$                   | Three phase |
| $Q_{noloadLoss} = \sqrt{(I_{ex} \times S_{rated})^2 - P_{noloadLoss}^2}$ | $Q_{noloadLoss} = 36.933 \text{ kVAR}$          | Three phase |
| $Q_{loadLoss} = \sqrt{(Z \times S_{rated})^2 - P_{loadLoss}^2}$          | $Q_{loadLoss} = 1.665 \times 10^3 \text{ kVAR}$ | Three Phase |

## Metering Data

$$CT_{ratio} = \frac{2500 \text{ A}}{5 \text{ A}} \quad \text{Line Current}$$

$$VT_{ratio} = \frac{2400 \text{ V}}{120 \text{ V}} \quad \text{Phase - Neutral}$$

Meter = Three Element

## Loss Coefficients

|  |   |           |
|--|---|-----------|
| $A = \frac{P_{noloadLoss}}{3} + \left( \frac{V_{itp}}{VT_{ratio}} \right)^2$ | $A = 384.153 \times 10^{-6} \frac{\text{kW}}{\text{V}^2}$   | Per Phase |
| $B = \frac{P_{loadLoss}}{3} + \left( \frac{I_{itp}}{CT_{ratio}} \right)^2$   | $B = 877.291 \times 10^{-3} \frac{\text{kW}}{\text{amp}^2}$ | Per Phase |
| $C = \frac{Q_{noloadLoss}}{3} + \left( \frac{V_{itp}}{VT_{ratio}} \right)^4$ | $C = 59.194 \times 10^{-9} \frac{\text{kVAR}}{\text{V}^4}$  | Per Phase |
| $D = \frac{Q_{loadLoss}}{3} + \left( \frac{I_{itp}}{CT_{ratio}} \right)^2$   | $D = 22.228 \frac{\text{kVAR}}{\text{amp}^2}$               | Per Phase |

**Figure B-10: Calculation of Loss Coefficients for the 18 MVA Transformer**

## B.5 Power Transformer with ULTC

In applications requiring voltage *regulation* or line drop compensation, power transformers are fitted with under load tap changers (ULTC). These are motor-driven devices that can alter the number of turns in either the low voltage or high voltage winding.

In addition, the winding without ULTC may also be fitted with fixed taps. For example, should the ULTC be on the secondary winding, the primary may have fixed tap positions.

CSA and ANSI standards require that impedance and load loss be determined at the principal and extreme taps.

Loss coefficients for transformers fitted with ULTC will be calculated based on the fixed tap used in operation and the average tap position of the ULTC. This would normally be determined by observation, documented in the periodic reading sheets and include seasonal variation. Linear interpolation would be applied if these positions are between tested positions. If reading sheets are not available, the fixed tap used in operation and the ULTC tap with the highest loss will be used as the basis for the calculation of loss coefficients.

The transformer for this example is rated at 50 MVA, 230/13.8 kV. The factory test results are as shown below.

| Load Loss (kW) |       |          |        |        |
|----------------|-------|----------|--------|--------|
| Fixed Tap      |       | ULTC Tap |        |        |
|                |       | 1        | 17     | 32     |
| Position       | kV    | 12.42    | 13.80  | 15.18  |
| 1              | 241.5 | 147.22   | 138.89 | 130.56 |
| 3              | 230.0 | 151.71   | 143.12 | 134.53 |
| 5              | 218.5 | 156.52   | 147.66 | 138.80 |

| Impedance (%) |       |          |       |       |
|---------------|-------|----------|-------|-------|
| Fixed Tap     |       | ULTC Tap |       |       |
|               |       | 1        | 17    | 32    |
| Position      | kV    | 12.42    | 13.80 | 15.18 |
| 1             | 241.5 | 11.00    | 10.70 | 10.44 |
| 3             | 230.0 | 11.02    | 10.70 | 10.43 |
| 5             | 218.5 | 11.12    | 10.80 | 10.53 |

| No Load Test |         |           |
|--------------|---------|-----------|
| Voltage      | Current | Loss (kW) |
| 100%         | 0.076%  | 35.60     |

**Figure B-11 Factory Test Results for the 50 MVA Power Transformer**

The high voltage winding is on service on tap 2 and the average tap position of the ULTC on the secondary winding is tap 28.

The *metering installation* is on the low voltage side and has three elements. The loss coefficients are calculated as shown in Figure B-12:

**Figure B-12: Calculation of Loss Coefficients for 50 MVA Power Transformer**

|   |                        |
|---|------------------------|
| $S_{\text{rated}} = 50 \text{ MVA}$       | Three phase            |
| $V_{\text{rated}} = 13.8 \text{ kV}$      | Line-Line on secondary |
| $P_{\text{noLoadLoss}} = 35.6 \text{ kW}$ | Loss at no load        |
| $I_{\text{ex}} = 0.076\%$                 | Exiting Current        |

Linear Interpolation for Off Nominal Tap

Load Loss on HV Tap 2 and LV Tap 28:

$$\begin{aligned}
 P_{2\_17} &= (138.89 + 143.12) \text{ kW} \div 2 & P_{2\_17} &= 141.005 \text{ kW} \\
 P_{2\_32} &= (130.56 + 134.53) \text{ kW} \div 2 & P_{2\_32} &= 132.545 \text{ kW} \\
 P_{\text{loadLoss}} &= P_{2\_17} + \left( \frac{P_{2\_32} - P_{2\_17}}{32 - 17} \right) (28 - 17) & P_{\text{loadLoss}} &= 134.801 \text{ kW}
 \end{aligned}$$

Impedance:

$$\begin{aligned}
 Z_{2\_17} &= (10.7\% + 10.7\%) \div 2 & Z_{2\_17} &= 10.7\% \\
 Z_{2\_32} &= (10.44\% + 10.43\%) \div 2 & Z_{2\_32} &= 10.435\% \\
 Z &= Z_{2\_17} + \left( \frac{Z_{2\_32} - Z_{2\_17}}{32 - 17} \right) (28 - 17) & Z &= 10.506\%
 \end{aligned}$$

$$CT_{\text{ratio}} = \frac{2000 \text{ A}}{5 \text{ A}} \quad \text{Line Current}$$

$$VT_{\text{ratio}} = \frac{8050 \text{ V}}{115 \text{ V}} \quad \text{Phase - Neutral}$$

Meter = Three Element

|  |  |             |
|--|--|-------------|
| $V_{\text{itp}} = V_{\text{rated}} \div \sqrt{3}$  | $V_{\text{itp}} = 7967.43 \text{ V}$                       | L-N         |
| $I_{\text{itp}} = S_{\text{rated}} \div (\sqrt{3} \times V_{\text{rated}})$                          | $I_{\text{itp}} = 2091.85 \text{ A}$                       | Three phase |
| $Q_{\text{noLoadLoss}} = \sqrt{(I_{\text{ex}} \times S_{\text{rated}})^2 - P_{\text{noLoadLoss}}^2}$ | $Q_{\text{noLoadLoss}} = 13.291 \text{ kVAR}$              | Three phase |
| $Q_{\text{loadLoss}} = \sqrt{(Z \times S_{\text{rated}})^2 - P_{\text{loadLoss}}^2}$                 | $Q_{\text{loadLoss}} = 5251.1 \text{ kVAR}$                | Three Phase |
| $A = \frac{P_{\text{noLoadLoss}}}{3} \div \left( \frac{V_{\text{itp}}}{VT_{\text{ratio}}} \right)^2$ | $A = 915.984 \times 10^{-6} \frac{\text{kW}}{\text{V}^2}$  | Per Phase   |
| $B = \frac{P_{\text{loadLoss}}}{3} \div \left( \frac{I_{\text{itp}}}{CT_{\text{ratio}}} \right)^2$   | $B = 1.643 \times 10^0 \frac{\text{kW}}{\text{amp}^2}$     | Per Phase   |
| $C = \frac{Q_{\text{noLoadLoss}}}{3} \div \left( \frac{V_{\text{itp}}}{VT_{\text{ratio}}} \right)^4$ | $C = 26.396 \times 10^{-9} \frac{\text{kVAR}}{\text{V}^4}$ | Per Phase   |
| $D = \frac{Q_{\text{loadLoss}}}{3} \div \left( \frac{I_{\text{itp}}}{CT_{\text{ratio}}} \right)^2$   | $D = 64.001 \frac{\text{kVAR}}{\text{amp}^2}$              | Per Phase   |

## B.6 Calculation Of Loss Coefficients When Factory Test Results Are Unavailable

### B.6.1 Requirement for Loss Coefficients

The loss coefficients for power transformers are normally calculated based on iron and copper losses measured in the factory at the time of manufacture. Since factory test results are not available for all power transformers, the SSLA Standard requires the application of standardized assumptions.

This section shows how loss coefficients may be calculated for power transformers when factory test results are unavailable.

### B.6.2 Default Assumptions for Power Transformers Losses

The standard assumptions for losses in power transformers are as follows:

|                                 |      |
|---------------------------------|------|
| Active Power Loss at Rated Load | 0.7% |
| Active Power Loss at No-Load    | 0.3% |
| Reactive Power Loss at No-Load  | 1.5% |

This data is combined with information available on the nameplate of the transformer. Together the two sets of information provide the details required for calculating the required loss coefficients.

### B.6.3 Other Transformer Information Required

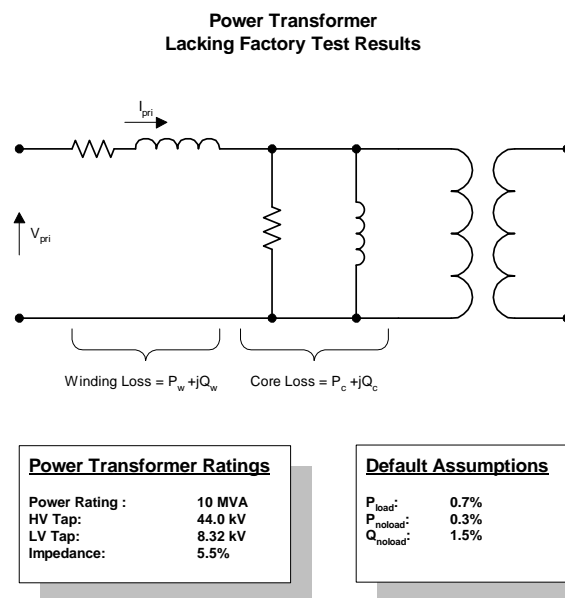
Both CSA and ANSI standards require that the following information be displayed on the nameplate of the power transformer and the nameplates of the *instrument transformers* connected to the metering.

|                                 |                          |
|---------------------------------|--------------------------|
| Apparent Power Rating           | kVA or MVA               |
| Rated High Voltage              | kV phase to phase        |
| Rated Low Voltage               | kV phase to phase        |
| Impedance on Short Circuit Test | Percent of rated voltage |
| Current transformer ratio       | To 5A Secondary          |
| Voltage transformer ratio       | To 120V Secondary        |

## B.6.4 Equivalent Circuit

Shown below is the equivalent circuit upon which the loss coefficients are calculated. The no-load losses occur in the core of the transformer. No-load loss is often termed iron loss or core loss. No-load losses are a function of the voltage applied to the power transformer.

The load loss occurs in the windings and is often termed copper loss or winding loss. Load loss is a function of the current delivered by the power transformer.



**Figure B-13: Default Assumptions when Factory Test Results are Unavailable**

## B.6.5 Example of Steps for Calculation of Loss Coefficients when Factory Test Data is not Available

The loss coefficients are calculated as constants of proportionality based on the losses at the rated load.

Step1: Gather name plate data: %Z, MVA, Primary & Secondary Voltage in kV Line to Line:

$$Z_{SC} = 5.5\%$$

$$S_{Rated} = 10MVA$$

$$V_{Pri} = 44.0kV$$

$$V_{Sec} = 8.32kV$$

Step2: The metering standards require the following standardized assumptions:

$$P_{noload} = 0.3\%$$

$$P_{load} = 0.7\%$$

$$Q_{noload} = 1.5\%$$

Step3: Calculate the Active core or no-load loss:

$$P_{noloadloss} = P_{noload} \times S_{rated}$$

$$P_{noloadloss} = 30.0 \text{ kW}$$

Step4: Calculate the Active winding or load loss:

$$P_{loadloss} = P_{load} \times S_{rated}$$

$$P_{loadloss} = 70.0 \text{ kW}$$

Step5: Calculate the Reactive core or no-load loss:

$$Q_{noloadloss} = Q_{noload} \times S_{rated}$$

$$Q_{noloadloss} = 150.0 \text{ kVAR}$$

Step6: Calculate the Active winding or load loss:

$$Q_{loadLoss} = \sqrt{(Z \times S_{rated})^2 - P_{loadLoss}^2}$$

$$Q_{loadLoss} = 545.527 \text{ kVAR}$$

**Figure B-14: Calculation of Loss Coefficients when Transformer Factory Test Data is not Available (Steps 1 to 6)**

Step7: Calculate the Loss Coefficients for Power Transformer:

$$CT_{\text{ratio}} = \frac{600 \text{ A}}{5 \text{ A}} \quad \text{Line Current}$$

$$VT_{\text{ratio}} = \frac{4800 \text{ V}}{120 \text{ V}} \quad \text{Phase - Neutral}$$

### Meter = Three Element

$$V_{\text{itp}} = V_{\text{rated}} \div \sqrt{3} \quad V_{\text{itp}} = 4803.55 \text{ V} \quad \text{L - N}$$

$$I_{\text{itp}} = S_{\text{rated}} \div (\sqrt{3} \times V_{\text{rated}}) \quad I_{\text{itp}} = 693.93 \text{ A} \quad \text{Three phase}$$

$$A = \frac{P_{\text{noloadLoss}}}{3} \div \left( \frac{V_{\text{itp}}}{VT_{\text{ratio}}} \right)^2 \quad A = 693.418 \times 10^{-6} \frac{\text{kW}}{\text{V}^2} \quad \text{Per Phase}$$

$$B = \frac{P_{\text{loadLoss}}}{3} \div \left( \frac{I_{\text{itp}}}{CT_{\text{ratio}}} \right)^2 \quad B = 697.763 \times 10^{-3} \frac{\text{kW}}{\text{amp}^2} \quad \text{Per Phase}$$

$$C = \frac{Q_{\text{noloadLoss}}}{3} \div \left( \frac{V_{\text{itp}}}{VT_{\text{ratio}}} \right)^4 \quad C = 240.414 \times 10^{-9} \frac{\text{kVAR}}{\text{V}^4} \quad \text{Per Phase}$$

$$D = \frac{Q_{\text{loadLoss}}}{3} \div \left( \frac{I_{\text{itp}}}{CT_{\text{ratio}}} \right)^2 \quad D = 5437.84 \times 10^{-3} \frac{\text{kVAR}}{\text{amp}^2} \quad \text{Per Phase}$$

**Figure B-15: Calculation of Loss Coefficients when Transformer Factory Test Data is not Available (Step 7)**

## B.7 Existing Metering Does Not Record amp-squared-hours, volt-squared-hours

*Meters* that were in service on April 17, 2000 or that are part of a *metering installation* that was the subject of an application for registration prior to the *market commencement date*, and for which major components were ordered or procured prior to April 17, 2000, and which do not record amp-squared-

hours, volt-squared-hours or kVARH need not be replaced until the Measurement Canada seal expires. (Chapter 6-Appendices, Appendix 6.2, Section 1.1.1 and 1.1A)

For these *metering installations*, the *IESO* will use, for calculation purposes, **the Assumed Voltage**, where secondary voltage, assumed power factor, service type, ct ratio and pt ratio are provided by the *Metering Service Provider*. The *IESO* software system will then calculate both amp-squared-hours and volt-squared-hours for each interval. A secondary voltage of 120 volts and a power factor of 0.95 will be used as default values, if not specified.

This calculation will also be used when the Main *meter* fails (amp-squared-hours and/or volt-squared-hours are not available). This calculation only applies to Method 1.

## **B.8 Connected Transformation Serving a Single Metered Market Participant**

### **B.8.1 Introduction**

The most common multi-transformer installation is the “Jones” station, or the dual element spot network (DESN). The DESN is a load serving *facility* consisting of two power transformers supplied from different high voltage circuits. The secondaries are bussed together through a normally closed breaker.

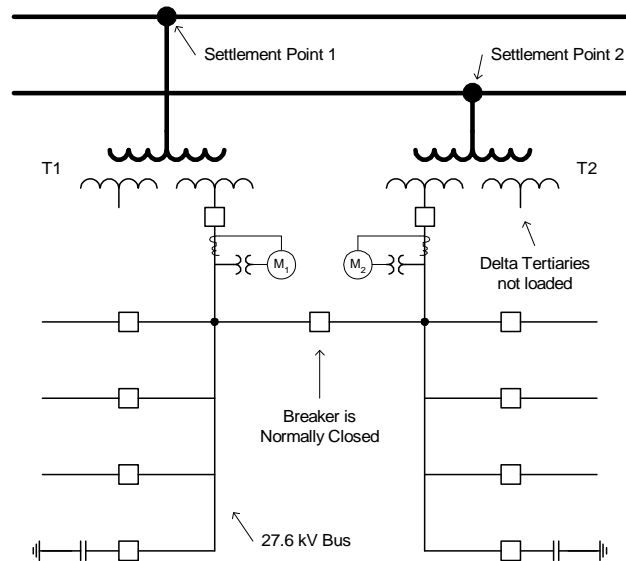
The *facility* has two *defined meter points*, both located on the high voltage side of the power transformers. Revenue metering may be installed at the *defined meter point*, in which case no site specific loss adjustments are required. This method is to be applied when revenue metering is installed on the low voltage side of a power transformer.

The *IESO* requires individual metering to be installed on each power transformer when the *metering installations* is installed on the low voltage side of a DESN substation. Loss adjustments for such installations are the same as for single transformer installations.

### **B.8.2 Individually Metered Power Transformers**

Figure B-16, below, illustrates the individual metering at a DESN substation.





**Figure B-16: Typical Metering Installation at a DESN Station**

### B.8.3 Loss Calculation At The IESO

For *settlement* purposes, the total *energy* consumption at each point of sale must be calculated. This calculation comprises the metered *energy* and the losses in the power transformer connected to each *defined meter point*.

Loss coefficients are developed for each power transformer based on the factory test data. The amp squared hours and volt squared hours recorded by the *metering installation* are used to calculate the losses in each power transformer as part of the *settlement process*. The calculated losses are added to the metered *energy* in order to obtain the total consumption at each *defined meter point*.

### B.8.4 Factory Test Data for Power Transformers

Factory test data for the power transformers at the DESN station in Figure B-19 is provided below, together with the operating tap positions.

| Parameter               | Transformer 1     | Transformer 2     |
|-------------------------|-------------------|-------------------|
| MVA Rating              | 50 MVA            | 50 MVA            |
| Rated Primary Voltage   | 230 kV            | 230 kV            |
| Rated Secondary Voltage | 27.6 kV           | 27.6 kV           |
| High Voltage Taps       | ± 10% in 4 Steps  | ± 10% in 4 Steps  |
| Secondary ULTC          | ± 10% in 32 Steps | ± 10% in 32 Steps |
| HV Tap Position         | Tap 4 (235.75 kV) | Tap 4 (235.75 kV) |
| Most Frequent LV Tap    | Tap 25 (28.98 kV) | Tap 25 (28.98 kV) |

The losses and impedance depend on the high voltage fixed tap position and the most frequently occurring ULTC tap position. The table below shows the data listed in the factory test results for each power transformer on the operating tap positions of HV Tap 4 and LV Tap 25:

| Parameter         | Transformer 1 | Transformer 2 |
|-------------------|---------------|---------------|
| Impedance on Taps | 15.68%        | 15.71%        |
| No-Load kW Loss   | 0.033%        | 0.032%        |
| No-Load kVAR Loss | 1.432%        | 1.453%        |
| Load kW Loss      | 0.371%        | 0.393%        |

### B.8.5 Loss Coefficients for the Power Transformers

Based on the factory test results for Transformer 1::

$$\text{Step1: } Z_{SC} = 15.68\% \quad S_{\text{Rated}} = 50\text{MVA} \quad V_{\text{Pri}} = 235.75\text{kV} \quad V_{\text{Sec}} = 28.98\text{kV}$$

$$\text{Step2: } P_{\text{noLoad}} = 0.033\% \quad P_{\text{load}} = 0.371\% \quad Q_{\text{noLoad}} = 1.432\%$$

$$\text{Step3: } P_{\text{noLoadLoss}} = P_{\text{noLoad}} \times S_{\text{rated}} \quad P_{\text{noLoadLoss}} = 16.5 \text{ kW}$$

$$\text{Step4: } P_{\text{loadLoss}} = P_{\text{load}} \times S_{\text{rated}} \quad P_{\text{loadLoss}} = 185.5 \text{ kW}$$

$$\text{Step5: } Q_{\text{noLoadLoss}} = Q_{\text{noLoad}} \times S_{\text{rated}} \quad Q_{\text{noLoadLoss}} = 716.0 \text{ kVAR}$$

$$\text{Step6: } Q_{\text{loadLoss}} = \sqrt{(Z \times S_{\text{rated}})^2 - P_{\text{loadLoss}}^2} \quad Q_{\text{loadLoss}} = 7837.80 \text{ kVAR}$$

#### Metering Data

$$CT_{\text{ratio}} = \frac{1000 \text{ A}}{5 \text{ A}} \quad VT_{\text{ratio}} = \frac{16800 \text{ V}}{120 \text{ V}} \quad \text{Meter} = \text{Three Element}$$

$$V_{\text{itp}} = V_{\text{rated}} \div \sqrt{3} \quad V_{\text{itp}} = 16.7316 \text{ kV}$$

$$I_{\text{itp}} = S_{\text{rated}} \div (\sqrt{3} \times V_{\text{rated}}) \quad I_{\text{itp}} = 996.118 \text{ A}$$

Follow same steps, for Transformer 2

Therefore, the loss coefficients required for *settlement* purposes are as follows:

| Coefficient | Transformer 1 | Transformer 2 | Unit                  |
|-------------|---------------|---------------|-----------------------|
| A           | 385.073E-6    | 373.404E-6    | kW/V <sup>2</sup>     |
| B           | 2.4926        | 2.6405        | kW/Amp <sup>2</sup>   |
| C           | 1.1699E-6     | 1.1871E-6     | kVAR/V <sup>4</sup>   |
| D           | 105.3201      | 105.5181      | kVAR/Amp <sup>2</sup> |

## B.8.6 Current Transformer Summated DESN Station

### Background

At certain DESN transformer stations built before April 17, 2000, current transformer summation was used to measure the “station total” consumption.

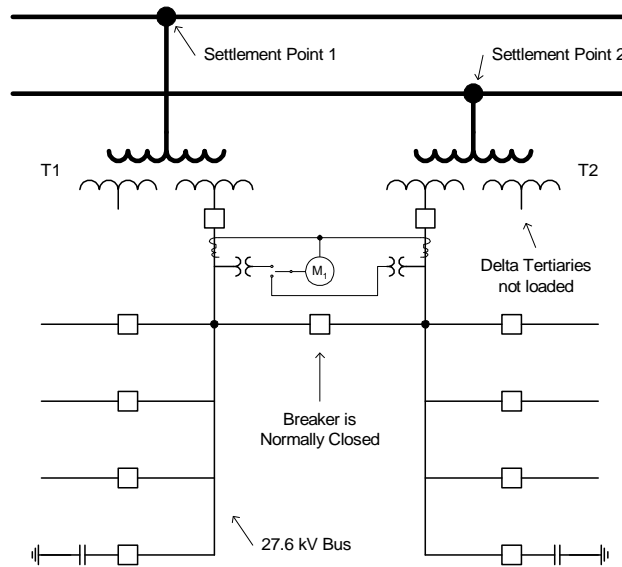
### Division of Load

The total power measured by the *meter* is assumed to be carried in fixed proportions by each of the two power transformers. At the DESN station shown in figure B-17, transformer T1 is observed to carry 48% on the total current delivered to the 27.6 kV bus.

In the absence of better information, the *IESO* will assume that the current divides equally between power transformers of the same MVA rating.

### Meter Connection Diagram

The figure below illustrates the current transformer summated metering *connection*:



**Figure B-17: Current Transformer Summated Metering Installation**

– End of Section –



# Appendix C: Method 2 - Equation Coefficients (K1, K2, K3)

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## C.1 Estimating Transformer Losses

### Introduction to Transformer Loss Calculation

For most transformer loss calculations the primary voltage is known. The kW and kVAR loads at the secondary and tertiary terminals are also known. An iterative solution can thus be applied to find the voltage and current to derive the power losses at each of the secondary and tertiary terminals. Once a solution is found, the losses can be calculated as the difference between the power in and the power out. Alternatively the  $I^2R$  and  $I^2X$  in each branch of the circuit can be summed to arrive at the transformer losses.

Power transformers are affected by iron and copper losses. Iron loss is also known as core loss or excitation. Copper losses are often termed winding loss or load loss.

Transformers are tested in the factory to establish the load and excitation losses. Load losses are measured by testing pairs of windings and recording the results of each test in the factory test report. Before loss calculations can be carried out, the "pair wise" test results must be converted into equivalent TEE impedances which will carry the specified loads to the secondary and tertiary terminals. Losses can be calculated directly from the TEE equivalent but this is not illustrated in this paper.

The format of the test results is standardized by ANSI. For load losses the percentage impedance and watt loss are reported for each winding pair. The percentage impedance is usually based on the ratings of the primary winding for tests involving it and on the ratings of the secondary winding for the remaining test.

Excitation losses are measured by energizing one of the windings to full rated voltage, with the other remaining open, then measuring the exciting current as a percentage of the rated current for the winding and the watt loss.

### C.1.1 Operation of Transformers in Parallel

If two or more transformers operate in parallel, the standard power flow equations may be used to calculate losses. Example 3 demonstrates the use of the bus admittance power flow equations for loss calculation.

Application of the bus admittance model requires that the TEE impedances be converted into branch impedances that directly *connect* the primary, secondary and tertiary nodes. The wye-delta transform is applied to eliminate the common *connection point* of the equivalent TEE impedances. Note that the pair-wise test results and the equivalent delta impedances do not take on the same numeric values.

## C.2 No-Load Loss

### Excitation Loss

The CSA Standard C88 defines the excitation loss of a transformer to be the active power absorbed by the transformer when rated voltage is applied at rated frequency to the terminals of one of the windings, all others being open circuited. The excitation loss includes the active power required to overcome hysteresis loss in the iron core, dielectric loss, and the  $I^2R$  loss caused by the exciting current.

### Exciting Current

The exciting current is defined in the C88 Standard as the current flowing through a line terminal when rated voltage is applied at rated frequency, all other windings being open circuited.

### Excitation Loss and Exciting Current Tests

The excitation loss and exciting current are measured in the factory at the time of manufacture. Rated voltage is applied to one of the windings with all of the others open circuited. Before the test commences each winding is placed on the principal tap position. The principal tap position is the rated voltage that will appear on the transformer nameplate.

The factory test records:

- the active power loss in watts, and
- the exciting current stated in amperes or as a percentage of the stated base current, usually the rated current for the winding being energized. The rated current is calculated from the rated kVA or MVA and rated voltage.

The test is repeated at 110% of rated voltage. Most manufacturers do not record the active power loss at this voltage.

Harmonic content is unavoidable, so results are stated on an equivalent sine-wave basis.

The no-load loss is independent of loading and is assumed to be constant as long as the excitation voltage is constant, regardless of which winding supplies the excitation *energy*.

### No-Load Loss

The no-load loss is the phasor power representing the sum of the active and reactive power required to excite the iron core. The no-load loss is often in a per unit or percentage basis of the rated MVA and rated kV of the highest voltage winding.

## Variation with Voltage

The active power loss varies as  $V^X$  where X varies from 1.6 to approximately 4 depending on the type of magnetic material and method of manufacture. Since the watt loss for most transformers is recorded only at nominal voltage, the true value at any other voltage cannot be determined. For this reason the revenue metering industry has standardized on the assumption that X is equal to 2.0.

The reactive power consumed by the core is also a function of voltage and varies as  $V^Y$  where Y varies from 2 to approximately 16, depending on the type of magnetic material and method of manufacture. And because the watt loss at 110% of rated voltage is not recorded for most transformers, the true value of Y cannot be determined. For this reason, the industry has standardized on the assumption that Y takes the value 4.

## C.3 Load Loss

### Active Power Loss

The active power loss in the windings of a power transformer arise from  $I^2R$  loss in the windings and  $I^2R$  losses due to circulating current in parallel windings and core clamps, etc.

### Reactive Power Loss

The windings also consume reactive power. Some flux always leaks from the core and pass through the air to link with the winding. Because a portion of the path followed by the leakage flux is in the air, the permeability of the air dominates and the leakage reactance is linear thus showing almost none of the saturation or hysteresis expected from an iron cored inductor.

### Load Loss and Impedance Test

The load loss is determined in the factory by testing pairs of windings. Before the test all windings are placed on the principal tap position. One winding of the pair is shorted out and sufficient voltage is applied to the other to cause current, corresponding to some stated MVA base, to flow in the shorted winding. All other windings are open-circuited.

The C88 standard states that impedance voltage on any tap is expressed on a percentage or per unit basis of the rated voltage of the tap when current corresponding to the stated, although not necessarily rated, MVA base is circulating through the winding. Care must be taken when carrying out load flow and loss evaluation studies to ensure the MVA base is in the calculations.

Transformer manufacturers test the load loss and impedance voltage on the rated tap position and test for impedance voltage on the extreme tap positions. If the transformer is not operating on one of the tested tap positions, interpolation must be used to determine the percentage impedance on the actual tap position before any other calculations are carried out<sup>1</sup>. Load loss is recorded in watts and is not always recorded for tap positions other than the principal tap.

<sup>1</sup> The standard equation for converting percent impedance from one base to another ( $S_{New}V_{Old}^2/S_{Old}V_{New}^2 = Z_{BaseOld}/Z_{BaseNew}$ ) assumes the impedances on each tap are known and the base voltages are in the same ratio as the tapped voltages.



The impedance voltage for each pair of windings on the transformer nameplate is determined with all windings in at their principal tap positions. The applied voltage is adjusted until current corresponding to the lesser of the MVA ratings of the two windings flows through the winding that is shorted out.

The impedance voltage is usually expressed as a percentage of the rated voltage of the tap to which the voltage was applied. The MVA base used is stated.

The impedance voltage for each winding pair may also be adjusted to either the MVA base of the winding to which the voltage was applied or an MVA base common to all of the windings. The MVA base will be stated in the factory test results. Care must be used to ensure correct base values are used in load flow and loss studies.

The loss values shown on the factory test card for load loss and impedance are adjusted to reflect a winding temperature of the 85°C.

### **Variation with Voltage**

The active and reactive losses caused by the flow of load are proportional to the square of the current in each winding. Load loss is only approximately proportional to load MVA.

### **Modeling No-Load Loss**

If the power flow software being used for loss evaluation does not allow the no-load loss or be evaluated at a function of voltage, valid results can still be obtained. Evaluation of site specific losses requires that one of the windings be the slack bus in the analysis.

Since the slack bus operates at fixed voltage specified before the study begins, the active and reactive no-load losses can be evaluated at that voltage then applied to the slack bus as a fix load or as the equivalent linear shunt impedance.

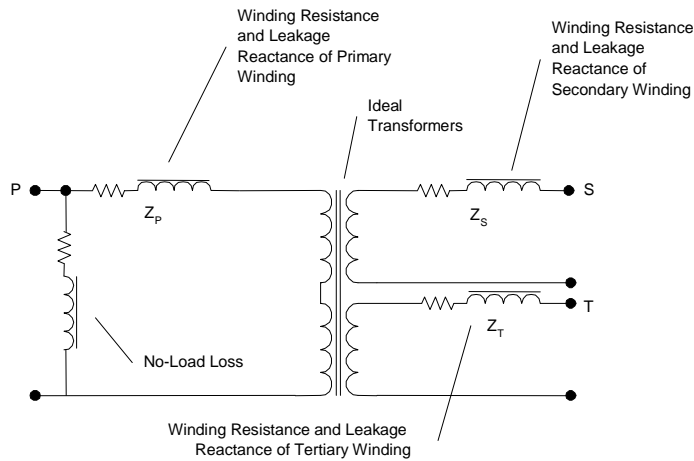
### **Example No-Load Loss Model**

The factory test report for a three winding 60/35/25 MVA 230/44/27.6 kV transformer lists the exciting current as 0.92% and the excitation loss as 53.2 kW. If a loss study were to be carried out with the voltage at the 44 kV winding fixed at 46.2 kV, the active power would be  $53.2 \text{ kW} \times (46.2/44)^2 = 58.65 \text{ kW}$ .

The apparent power loss at rated voltage would be  $0.92\% \times 60 \text{ MVA} = 552.0 \text{ kVA}$ . The reactive power loss at rated voltage is  $(552^2 - 58.65^2)^{1/2} = 548.9 \text{ kVAR}$ . The reactive power loss at 46.2 kV would be  $548.9 \times (46.2/44)^4 = 667.19 \text{ kVAR}$ .

### C.4 Equivalent TEE Branch Impedances

The equivalent circuit of one phase of a three-winding transformer is shown below:



**Figure C-1: Three Winding Transformer**

where P, S & T represent the primary, secondary and tertiary windings respectively and  $Z_p, Z_s, Z_t$  represent the resistance and reactance of each winding.

The factory tests carried out by the transformer manufacturer determine the total impedance between each pair of windings. These are:

**Table C-1: Measured Impedance**

| Winding Pair | Measured Impedance   |
|--------------|----------------------|
| PS           | $Z_{PS} = Z_p + Z_s$ |
| PT           | $Z_{PT} = Z_p + Z_t$ |
| TS           | $Z_{TS} = Z_t + Z_s$ |

For losses within the transformer to be modeled properly, the factory test results must be converted into equivalent branch impedances. The 1998 IEEE paper titled "Effect of Three-Winding Transformer Models on the Analysis and Protection of Mine Power Systems" by Oommen and Kohler<sup>2</sup> shows that significant error occurs when the transformer model uses the factory test results directly and the effect of changes in base MVA is ignored.

The TEE equivalent model of the leakage impedances can be calculated by solving the system of equations shown in Table B-1. If all of the leakage impedance figures listed in the factory test report are in percent or per unit on the same MVA base, result is:

<sup>2</sup> Available at <http://www.cdc.gov/niosh/ciss/pdfs/eotw.pdf>

**Table C-2: Per Cent or Per Unit Equations**

$$Z_P = \frac{1}{2} (Z_{PS} + Z_{PT} - Z_{ST})$$

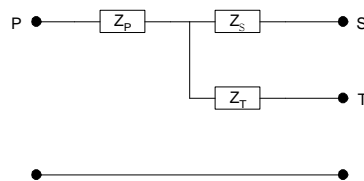
$$Z_S = \frac{1}{2} (Z_{PS} + Z_{ST} - Z_{PT})$$

$$Z_T = \frac{1}{2} (Z_{PT} + Z_{ST} - Z_{PS})$$

But transformer manufacturers often use the rated MVA of one of the windings in the winding pair being tested as the base MVA for the impedance test. As a result the impedances are usually on different bases. These impedances must be brought to a common base MVA before calculations can begin.

## C.5 TEE and Delta Models for Leakage Impedance

The equivalent TEE model is shown in Figure B-25. The leakage impedances for each winding are in per unit on the same MVA base. The primary, secondary and tertiary terminals are marked P, S and T respectively.

**Figure C-2: TEE Model of Transformer Leakage Impedance**

The loss in each winding can be calculated from the TEE impedances once the load and voltage at each terminal is determined. This is achieved by specifying the voltage at one terminal and the load on the other two terminals. The power flow equations are then solved to arrive at the voltage and load at all terminals.

When two or more transformers operating in parallel, application of the standard power flow models requires that the common *connection point* of the TEE impedances be eliminated. This is achieved through application of the wye-delta transform:

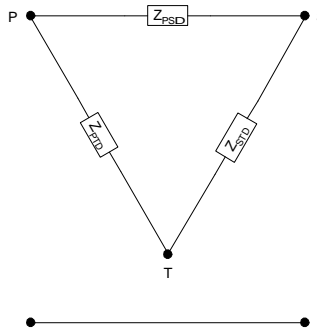
**Table C-3: Wye-Delta Transformation**

$$Z_{PS\Delta} = (Z_P \cdot Z_S + Z_S \cdot Z_T + Z_P \cdot Z_T) \div Z_T$$

$$Z_{PT\Delta} = (Z_P \cdot Z_S + Z_S \cdot Z_T + Z_P \cdot Z_T) \div Z_S$$

$$Z_{ST\Delta} = (Z_P \cdot Z_S + Z_S \cdot Z_T + Z_P \cdot Z_T) \div Z_P$$

where  $Z_{PS\Delta}$ ,  $Z_{PT\Delta}$ ,  $Z_{ST\Delta}$ , directly connect the P, S and T terminals as shown below:



**Figure C-3: Equivalent Delta Model for Leakage Impedance**

The wye-delta transformation is power invariant and the total *energy* loss is the same as in the TEE model.

Note that the delta impedances do not take on the same numeric values as the pair-wise impedances measured in the factory.

The bus admittance power flow model requires the delta impedances be converted into admittance values that are the reciprocal of the impedance value. The current in the P-S branch is then calculated as  $(V_P - V_S) \times Y_{PS}$  rather than  $(V_P - V_S) / Z_{PS}$ .

## C.6 Example Calculations for TEE Leakage Impedance

### Example 1

Assume we have a three winding transformer with the factory test results as shown below and that we wish to carry out power flow, short circuit or loss analysis on a 240 kV/100 MVA base. The transformer ratings are 60/35/25 MVA and 230/44/27.6 kV for the P, S and T windings respectively. The primary has 5 taps at 230, 235.75, 241.5, 247.25 and 253 kV. The transformer is operating on the 247.25 kV tap. The secondary and tertiary windings are not tapped and neither is fitted with ULTC.

| <b>Ratings</b>    |         |        |
|-------------------|---------|--------|
| Primary Winding   | 230 kV  | 60 MVA |
| Secondary Winding | 44 kV   | 35 MVA |
| Tertiary          | 27.6 kV | 25 MVA |

The factory test report shows the following results:

| <b>Test Report</b> |            |                               |        |                               |        |
|--------------------|------------|-------------------------------|--------|-------------------------------|--------|
| Winding Pair       | Load Loss  | Impedance                     | Tap    | Impedance                     | Tap    |
| P-S                | 374.291 kW | $Z_{PS} = 10.447\%$ on 60 MVA | 230 kV | $Z_{PS} = 10.878\%$ on 60 MVA | 253 kV |
| P-T                | 367.487 kW | $Z_{PT} = 21.400\%$ on 60 MVA | 230 kV |                               |        |
| S-T                | 53.261 kW  | $Z_{ST} = 2.862\%$ on 35 MVA  | 44 kV  |                               |        |

First, the impedances listed on the test report must be adjusted to reflect the actual operating taps. Since the primary winding is the only one operating in a position different than that shown on the factory test report, only  $Z_{PS}$  needs to be adjusted:

$$Z_{PS} = 10.447\% + (10.878\% - 10.447\%)*(247.25-230)/(253-230) = 10.77\%$$

**Example 1: Convert Factory Test Results to Branch Impedance in % on 240 kV and 100 MVA**

|  |  |                                      |   |   |
|--|--|--------------------------------------|---|---|
| <b>New Basis:</b>                            | $V_{\text{base}} = 240\text{ kV}$  | $S_{\text{base}} = 100\text{ MVA}$   | $Z_{\text{base}} = \frac{V_{\text{base}}^2}{S_{\text{base}}}$ |   |
| <b>Ratings:</b>                              | $V_P = 230\text{ kV}$  | $V_S = 44\text{ kV}$                 | $V_T = 26.7\text{ kV}$  |   |
|  | $S_P = 60\text{ MVA}$  | $S_S = 35\text{ MVA}$                | $S_T = 25\text{ MVA}$   |   |
| <b>Factory Test Results:</b>                 | $Z_{\text{PST}} = 10.77\%$ on 60 MVA and 230 kV  | $P_{\text{PST}} = 374.291\text{ kW}$ |   | <b>Note:</b> Tests were carried out at ratings of the windings: |
|  | $Z_{\text{PTT}} = 21.4\%$ on 60 MVA and 230 kV   | $P_{\text{PTT}} = 367.487\text{ kW}$ |   |   |
|  | $Z_{\text{STT}} = 2.862\%$ on 35 MVA and 44 kV   | $P_{\text{STT}} = 53.261\text{ kW}$  |   |   |
| <b>Calculate <math>Z_{\text{PS}}</math>:</b> | $R_{\text{PS}} = \frac{P_{\text{PST}}}{S_P}$   | $R_{\text{PS}} = 0.624\%$            |   | On 60 MVA   |
|  | $X_{\text{PS}} = \sqrt{Z_{\text{PST}}^2 - R_{\text{PS}}^2}$  | $X_{\text{PS}} = 10.752\%$           |   | On 60 MVA   |
|  | $Z_{\text{PS}} = (R_{\text{PS}} + j \cdot X_{\text{PS}}) \cdot \frac{S_{\text{base}}}{S_P} \cdot \left(\frac{V_P}{V_{\text{base}}}\right)^2$ |                                      | $Z_{\text{PS}} = 0.955 + 16.458j\%$                           | On 100 MVA & 240 kV   |
| <b>Calculate <math>Z_{\text{PT}}</math>:</b> | $R_{\text{PT}} = \frac{P_{\text{PTT}}}{S_P}$   | $R_{\text{PT}} = 0.612\%$            |   | On 60 MVA   |
|  | $X_{\text{PT}} = \sqrt{Z_{\text{PTT}}^2 - R_{\text{PT}}^2}$  | $X_{\text{PT}} = 21.391\%$           |   | On 60 MVA   |
|  | $Z_{\text{PT}} = (R_{\text{PT}} + j \cdot X_{\text{PT}}) \cdot \frac{S_{\text{base}}}{S_P} \cdot \left(\frac{V_P}{V_{\text{base}}}\right)^2$ |                                      | $Z_{\text{PT}} = 0.938 + 32.743j\%$                           | On 100 MVA & 240 kV   |
| <b>Calculate <math>Z_{\text{ST}}</math>:</b> | $R_{\text{ST}} = \frac{P_{\text{STT}}}{S_S}$   | $R_{\text{ST}} = 0.152\%$            |   | On 35 MVA   |
|  | $X_{\text{ST}} = \sqrt{Z_{\text{STT}}^2 - R_{\text{ST}}^2}$  | $X_{\text{ST}} = 2.858\%$            |   | On 35 MVA   |
|  | $Z_{\text{ST}} = (R_{\text{ST}} + j \cdot X_{\text{ST}}) \cdot \frac{S_{\text{base}}}{S_S} \cdot \left(\frac{V_P}{V_{\text{base}}}\right)^2$ |                                      | $Z_{\text{ST}} = 0.399 + 7.5j\%$                              | On 100 MVA & 240 kV   |
| <b>Calculate TEE Impedances:</b>             | $Z_P = 0.5 \cdot (Z_{\text{PS}} + Z_{\text{PT}} - Z_{\text{ST}})$  |                                      | $Z_P = 0.747 + 20.851j\%$                                     | On 100 MVA & 240 kV   |
|  | $Z_S = 0.5 \cdot (Z_{\text{PS}} + Z_{\text{ST}} - Z_{\text{PT}})$  |                                      | $Z_S = 0.208 - 4.392j\%$                                      | On 100 MVA & 240 kV   |
|  | $Z_T = 0.5 \cdot (Z_{\text{PT}} + Z_{\text{ST}} - Z_{\text{PS}})$  |                                      | $Z_T = 0.191 + 11.892j\%$                                     | On 100 MVA & 240 kV   |

Note that  $Z_S$  is negative. Zero and negative values are common and should be treated as such in loss calculations. The negative value does not represent a capacitor and the common *connection point* is not the system neutral.

## Example 2

In this example, the manufacturer has expressed the impedances for the transformer on the base values other than those of the windings. The 230 kV winding operates on the 230 kV tap and has an impedance of 2.244% on that tap at 12.5 MVA. Calculation of power flow, short circuit or loss analysis on a 240 kV and 100 MVA base is then required.

| Ratings           |         |        |
|-------------------|---------|--------|
| Primary Winding   | 230 kV  | 60 MVA |
| Secondary Winding | 44 kV   | 35 MVA |
| Tertiary          | 27.6 kV | 25 MVA |

The factory test report shows the following results:

| Load Loss Test Results |           |  |               |
|------------------------|-----------|--|---------------|
| Winding Pair           | Load Loss | Impedance                                | Operating Tap |
| P-S                    | 16.245 kW | $Z_{PS} = 2.244\%$ on 12.5 MVA and 44 kV | 44.0 kV       |
| P-T                    | 33.074 kW | $Z_{PT} = 6.42\%$ on 18 MVA and 27.6 kV  | 27.6 kV       |
| S-T                    | 8.895 kW  | $Z_{ST} = 1.115\%$ on 15 MVA and 28.0 kV | 27.6 kV       |

**Example 2: Convert Factory Test Results to Branch Impedance in % on 240 kV and 100 MVA**

|                                       |  |                      |  |  |
|---------------------------------------|--|----------------------|--|--|
| <b>New Basis:</b>                     | $V_{base} = 240.kV$  | $S_{base} = 100.MVA$ | $Z_{base} = \frac{V_{base}^2}{S_{base}}$ |  |
| <b>Ratings:</b>                       | $V_P = 230kV$  | $V_S = 44kV$         | $V_T = 26.7kV$                           |  |
|                                       | $S_P = 60MVA$  | $S_S = 35MVA$        | $S_T = 25MVA$                            | <b>Note:</b> Tests were not carried out ratings of the |
| <b>Factory Test Results:</b>          | $Z_{PST} = 2.244\%$ on 12.5 MVA and 44   | $P_{PST} = 16.245kW$ | $S_{PSB} = 12.5MVA$                      | $V_{PSB} = 44kV$                                       |
|                                       | $Z_{PTT} = 6.42\%$ on 18 MVA and 27.6  | $P_{PTT} = 33.074kW$ | $S_{PTB} = 18MVA$                        | $V_{PTB} = 26.7kV$                                     |
|                                       | $Z_{STT} = 1.115\%$ on 15 MVA and 28.0   | $P_{STT} = 8.895kW$  | $S_{STB} = 15MVA$                        | $V_{STB} = 28kV$                                       |
| <b>Calculate <math>Z_{PS}</math>:</b> | $R_{PS} = \frac{P_{PST}}{S_{PSB}}$   | $R_{PS} = 0.13\%$    |  | On 12.5 MVA and 44                                     |
|                                       | $X_{PS} = \sqrt{Z_{PST}^2 - R_{PS}^2}$   | $X_{PS} = 2.24\%$    |  | On 12.5 MVA and 44                                     |
|                                       | $Z_{PS} = (R_{PS} + j \cdot X_{PS}) \cdot \frac{S_{base}}{S_{PSB}} \cdot \left(\frac{V_P}{V_{base}}\right)^2 \cdot \left(\frac{V_{PSB}}{V_S}\right)^2$ |                      | $Z_{PS} = 0.955 + 16.458j\%$             | On 100 MVA & 240 kV                                    |
| <b>Calculate <math>Z_{PT}</math>:</b> | $R_{PT} = \frac{P_{PTT}}{S_{PTB}}$   | $R_{PT} = 0.184\%$   |  | On 18 MVA and 27.6                                     |
|                                       | $X_{PT} = \sqrt{Z_{PTT}^2 - R_{PT}^2}$   | $X_{PT} = 6.417\%$   |  | On 18 MVA and 27.6                                     |
|                                       | $Z_{PT} = (R_{PT} + j \cdot X_{PT}) \cdot \frac{S_{base}}{S_{PTB}} \cdot \left(\frac{V_P}{V_{base}}\right)^2 \cdot \left(\frac{V_{PTB}}{V_T}\right)^2$ |                      | $Z_{PT} = 0.938 + 32.743j\%$             | On 100 MVA & 240 kV                                    |
| <b>Calculate <math>Z_{ST}</math>:</b> | $R_{ST} = \frac{P_{STT}}{S_{STB}}$   | $R_{ST} = 0.059\%$   |  | On 15 MVA and 28                                       |
|                                       | $X_{ST} = \sqrt{Z_{STT}^2 - R_{ST}^2}$   | $X_{ST} = 1.114\%$   |  | On 15 MVA and 28                                       |
|                                       | $Z_{ST} = (R_{ST} + j \cdot X_{ST}) \cdot \frac{S_{base}}{S_{STB}} \cdot \left(\frac{V_P}{V_{base}}\right)^2 \cdot \left(\frac{V_{STB}}{V_T}\right)^2$ |                      | $Z_{ST} = 0.399 + 7.5j\%$                | On 100 MVA & 240 kV                                    |
| <b>Calculate TEE Impedances:</b>      | $Z_P = 0.5 \cdot (Z_{PS} + Z_{PT} - Z_{ST})$   |                      | $Z_P = 0.747 + 20.851j\%$                | On 100 MVA & 240 kV                                    |
|                                       | $Z_S = 0.5 \cdot (Z_{PS} + Z_{ST} - Z_{PT})$   |                      | $Z_S = 0.208 - 4.392j\%$                 | On 100 MVA & 240 kV                                    |
|                                       | $Z_T = 0.5 \cdot (Z_{PT} + Z_{ST} - Z_{PS})$   |                      | $Z_T = 0.191 + 11.892j\%$                | On 100 MVA & 240 kV                                    |



### Example 3: Evaluation of Loss in One Transformer

For the transformer in Example 1, determine the losses when the primary winding operates at 245 kV and the secondary and tertiary windings carry a range of loading. The secondary loads are typical of the loading experienced under actual operating conditions. Past readings were used to establish actual loads for the secondary and tertiary windings.

The MathCad spreadsheet below demonstrates the application of the bus admittance model and the solution of the power flow equations to the calculation of losses in one transformer.

The spreadsheet automates the calculation of total loss at each specified loading. Listed are the losses for five different load combinations applied to the secondary and tertiary windings. The user specifies the:

- base MVA and kV
- TEE impedance of each winding on the specified base
- voltage at the primary terminals
- MVA load and power factor on each of the secondary and tertiary terminals

at the top of the work sheet. The total loss is then read off at the bottom of the spreadsheet. Repeating the process for several other loads and pasting the results into the table results in the summary shown at the bottom of the spreadsheet.

**Example 3: Loss Calculation For One Transformer**

$S_{base} = 100 \cdot \text{MVA}$        $V_{base} = 240 \cdot \text{kV}$

Specify base quantities here.

$S_S = -\left(\frac{30 \cdot \text{MVA}}{S_{base}} \cdot e^{j\text{acos}(0.9)}\right)$        $S_T = -\left(\frac{25 \cdot \text{MVA}}{S_{base}} \cdot e^{j\text{acos}(0.89)}\right)$        $V_P = \frac{245 \cdot \text{kV}}{V_{base}} \cdot \text{pu}$

Specify  $V_P$ , S & T loads here.  
Use - for loads, + for generators

$S_{NoLoad} = \left[ 53.2 \cdot \text{kW} \cdot \left(\frac{V_{base} \cdot |V_P|}{230 \cdot \text{kV}}\right)^2 + j \cdot 548.9 \cdot \text{kVAR} \cdot \left(\frac{V_{base} \cdot |V_P|}{230 \cdot \text{kV}}\right)^4 \right] + S_{base}$

Specify no-load loss at rated voltage here.

$Z_P = (0.747 + j \cdot 20.851)\%$        $Z_S = (0.208 - j \cdot 4.392)\%$        $Z_T = (0.191 + j \cdot 11.892)\%$

Specify TEE equivalent transformer Z's here.

$Z_{PS\Delta} = (Z_P \cdot Z_S + Z_S \cdot Z_T + Z_P \cdot Z_T) \div Z_T$        $Z_{PS\Delta} = 0.012 + 0.087j$        $Y_{PS} = Z_{PS\Delta}^{-1}$   
 $Z_{PT\Delta} = (Z_P \cdot Z_S + Z_S \cdot Z_T + Z_P \cdot Z_T) \div Z_S$        $Z_{PT\Delta} = -0.047 - 0.234j$        $Y_{PT} = Z_{PT\Delta}^{-1}$   
 $Z_{ST\Delta} = (Z_P \cdot Z_S + Z_S \cdot Z_T + Z_P \cdot Z_T) \div Z_P$        $Z_{ST\Delta} = 0.006 + 0.05j$        $Y_{ST} = Z_{ST\Delta}^{-1}$

Convert TEE equivalent into delta equivalent via wye-delta transform & find bus admittance

$V_S = 1 \cdot \text{pu}$        $V_T = 1 \cdot \text{pu}$

Standard starting point for unknown voltages

Given  $\overline{S_S} + \overline{V_S} = -Y_{PS} \cdot V_P + (Y_{PS} + Y_{ST}) \cdot V_S - Y_{ST} \cdot V_T$

Power flow equations in standard bus admittance format

$\overline{S_T} + \overline{V_T} = -Y_{PT} \cdot V_P - Y_{ST} \cdot V_S + (Y_{ST} + Y_{PT}) \cdot V_T$

$\begin{pmatrix} V_S \\ V_T \end{pmatrix} = \text{Find}(V_S, V_T)$        $V_S = 0.96 - 0.087j$        $V_T = 0.935 - 0.125j$

Power flow solution for S & T bus voltages

$I_S = Y_{PS} \cdot (V_P - V_S) + Y_{ST} \cdot (V_T - V_S)$        $I_T = Y_{PT} \cdot (V_P - V_T) + Y_{ST} \cdot (V_S - V_T)$        $I_P = I_S + I_T$       Calculate bus currents from converged solution

Check Solution:  $|V_S \cdot \overline{I_S}| \cdot S_{base} = 30 \text{ MVA}$        $|V_T \cdot \overline{I_T}| \cdot S_{base} = 25 \text{ MVA}$   
 $\cos(\text{angle}(V_S \cdot \overline{I_S})) = 0.91$        $\cos(\text{angle}(V_T \cdot \overline{I_T})) = 0.89$

Ok: Converged solution matches specified load MVAs and specified power factors

Calculate Losses at specified load:

$S_{LoadLoss} = V_P \cdot \overline{I_P} - V_S \cdot \overline{I_S} - V_T \cdot \overline{I_T}$        $S_{LoadLoss} = 0.281 + 7.32j\%$

Loss = power in - power out

Check:  $|I_P|^2 \cdot Z_P + |I_S|^2 \cdot Z_S + |I_T|^2 \cdot Z_T = 0.281 + 7.32j\%$

OK: sum of  $I^2Z = P_{in} - P_{out}$

$S_{LossTotal} = S_{NoLoad} + S_{LoadLoss}$        $S_{LossTotal} = 0.342 + 8.027j\%$

Losses calculated at:

**Load Loss:**       $S_{LoadLoss} \cdot S_{base} = 281.151 + 7320.161j \text{ kVA}$   
**No-Load Loss:**       $S_{NoLoad} \cdot S_{base} = 60.365406 + 706.718116j \text{ kVA}$   
**Total Loss:**       $S_{LossTotal} \cdot S_{base} = 341.516 + 8026.879j \text{ kVA}$

$V_P \cdot V_{base} = 245 \text{ kV}$

$|S_S \cdot S_{base}| = 30 \text{ MVA}$

$|S_T \cdot S_{base}| = 25 \text{ MVA}$

Losses at other load combinations on the S & T terminals

**SUMMARY TABLE OF RESULTS**

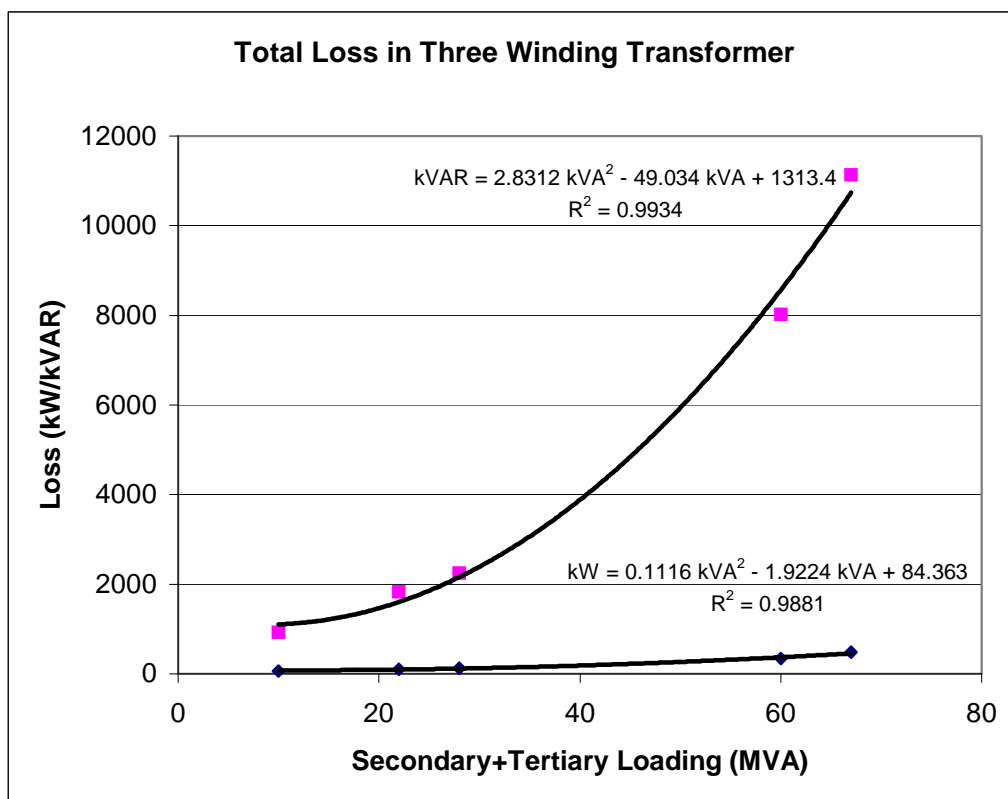
| MVA |    | PF   |      | Total Loss |            |
|-----|----|------|------|------------|------------|
| T   | S  | T    | S    | kW         | kVAR       |
| 5   | 5  | 0.85 | 0.91 | 68.647     | 929.115j   |
| 10  | 12 | 0.97 | 0.88 | 100.902    | 1832.252j  |
| 20  | 8  | 0.92 | 0.94 | 128.884    | 2252.876j  |
| 35  | 25 | 0.91 | 0.89 | 341.516    | 8026.879j  |
| 40  | 27 | 0.93 | 0.96 | 477.684    | 11131.188j |

The summary table of the spreadsheet of Example 3 was completed by typing the specified loads and power factors into the variables  $S_S$  and  $S_T$  above and pasting the converged solution from  $S_{LossTotal}$  back into the matrix. The matrix was then pasted into an Excel spreadsheet and the total kVA in the S and T winding summed in a new column. The total kVA was then plotted against the active and reactive power losses as an X-Y scatter chart without lines joining the plotted points.

Excel's curve fitting routine is then used to draw the lines joining the points and calculate the coefficients shown below. These coefficients are submitted to the IESO when application of Method 2 is required for loss adjustments. The IESO will read the meters installed on the S and T windings, sum them and then compute the total loss in the transformer.

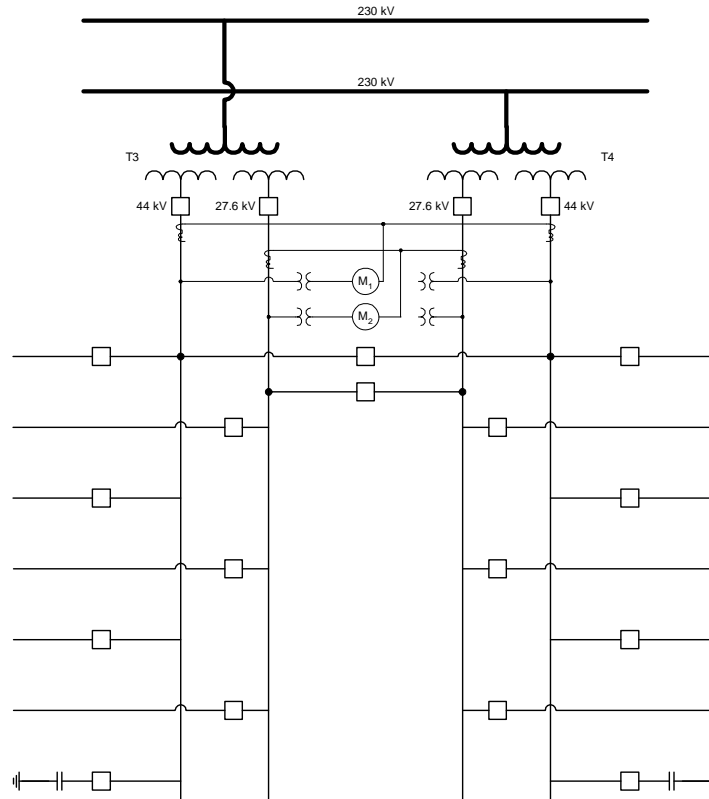
The  $R^2$  value shown on the graph is a measure of best fit and takes on values that range from zero to one. A value between 0.95 and 1.0 indicates that total kVA can be used to reliably predict losses.

| T MVA | S MVA | Total | kW Loss | kVAR Loss |
|-------|-------|-------|---------|-----------|
| 5     | 5     | 10    | 68.647  | 929.115   |
| 10    | 12    | 22    | 100.902 | 1832.252  |
| 20    | 8     | 28    | 128.884 | 2252.876  |
| 35    | 25    | 60    | 341.516 | 8026.879  |
| 40    | 27    | 67    | 477.684 | 11131.188 |



### Example 4: Loss Calculation for Transformers Operating in Parallel

Three winding transformers are often used in a double bus configuration as illustrated below.



**Figure C-4: Double Bus Transformer Station**

The ratings for both transformers are as shown below:

| Ratings T3 & T4   |         |        |
|-------------------|---------|--------|
| Primary Winding   | 230 kV  | 60 MVA |
| Secondary Winding | 44 kV   | 35 MVA |
| Tertiary          | 27.6 kV | 25 MVA |

The no-load losses are:

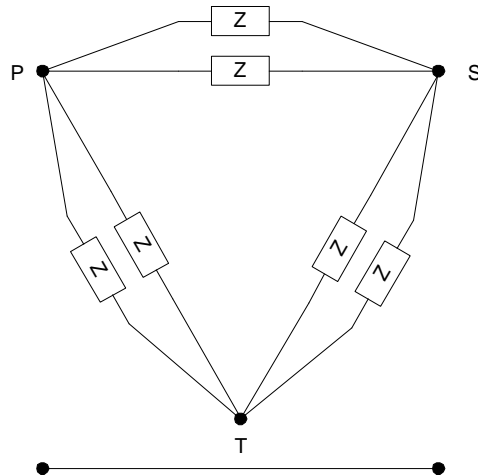
| Excitation Test Results for T3 & T4 |        |        |
|-------------------------------------|--------|--------|
|                                     | T3     | T4     |
| kW                                  | 53.2   | 55.3   |
| KVAR                                | 549.43 | 579.36 |
| % $I_{ex}$                          | 0.92   | 0.97   |

| <b>Load Loss Test Results for T3</b> |            |                               |        |
|--------------------------------------|------------|-------------------------------|--------|
| Winding Pair                         | Load Loss  | Impedance                     | Tap    |
| P-S                                  | 374.291 kW | $Z_{PS} = 10.770\%$ on 60 MVA | 230 kV |
| P-T                                  | 367.487 kW | $Z_{PT} = 21.400\%$ on 60 MVA | 230 kV |
| S-T                                  | 53.261 kW  | $Z_{ST} = 2.862\%$ on 35 MVA  | 44 kV  |
| <b>Load Loss Test Results for T4</b> |            |                               |        |
| Winding Pair                         | Load Loss  | Impedance                     | Tap    |
| P-S                                  | 380.223 kW | $Z_{PS} = 10.750\%$ on 60 MVA | 230 kV |
| P-T                                  | 386.835 kW | $Z_{PT} = 21.450\%$ on 60 MVA | 230 kV |
| S-T                                  | 61.282 kW  | $Z_{ST} = 2.871\%$ on 35 MVA  | 44 kV  |

The TEE impedances on 240 kV and 100 MVA are:

| <b>TEE Impedance for T3 &amp; T4</b> |                   |                   |
|--------------------------------------|-------------------|-------------------|
| Winding Pair                         | T3                | T4                |
| P-S                                  | 0.747 +j 20.851 % | 0.749 +j 20.862 % |
| P-T                                  | 0.208 -j 4.392 %  | 0.221 -j 4.436 %  |
| S-T                                  | 0.191 +j 11.892 % | 0.238 +j 11.956 % |

The equivalent delta circuit for the T3 and T4 is as shown below.



The *meters* measure the total flow from each of the secondary and tertiary windings. The average voltage at the primary windings is 245 kV.

The spreadsheet following illustrates the calculations and lists the losses over a range of values taken from past reading sheets.

**Example 4: Loss Calculation For Double Winding Transformer**

$S_{base} = 100 \cdot \text{MVA}$        $V_{base} = 240 \cdot \text{kV}$

$Z_{P1} = (0.747 + j \cdot 20.851)\%$      $Z_{S1} = (0.208 - j \cdot 4.392)\%$      $Z_{T1} = (0.191 + j \cdot 11.892)\%$

$Z_{P2} = (0.747 + j \cdot 20.851)\%$      $Z_{S2} = (0.208 - j \cdot 4.392)\%$      $Z_{T2} = (0.191 + j \cdot 11.892)\%$

$S_S = -\left(\frac{70 \cdot \text{MVA}}{S_{base}} \cdot e^{j \cos(0.9)}\right)$      $S_T = -\left(\frac{50 \cdot \text{MVA}}{S_{base}} \cdot e^{j \cos(0.89)}\right)$      $V_P = \frac{245 \cdot \text{kV}}{V_{base}} \cdot \text{pu}$

Specify base quantities here.

Specify TEE equivalent transformer Z's here.

Specify  $V_P$ , S & T loadshare, - for loads, + for generators

$S_{NoLoad} = \left[ (53.2 + 55.3) \cdot \text{kW} \cdot \left(\frac{V_{base} \cdot |V_P|}{230 \cdot \text{kV}}\right)^2 + j \cdot (549.43 + 579.36) \cdot \text{kVAR} \cdot \left(\frac{V_{base} \cdot |V_P|}{230 \cdot \text{kV}}\right) \right] + S_{base}$     Specify no-load loss at rated voltage

$Z_{PS\Delta 1} = (Z_{P1} \cdot Z_{S1} + Z_{S1} \cdot Z_{T1} + Z_{P1} \cdot Z_{T1}) \div Z_{T1}$      $Z_{PS\Delta 1} = 0.012 + 0.087j$      $Y_{PS1} = Z_{PS\Delta 1}^{-1}$

Convert TEE equivalent into delta equivalent via wye-delta transform & find bus admittance for T1

$Z_{PT\Delta 1} = (Z_{P1} \cdot Z_{S1} + Z_{S1} \cdot Z_{T1} + Z_{P1} \cdot Z_{T1}) \div Z_{S1}$      $Z_{PT\Delta 1} = -0.047 - 0.234j$      $Y_{PT1} = Z_{PT\Delta 1}^{-1}$

$Z_{ST\Delta 1} = (Z_{P1} \cdot Z_{S1} + Z_{S1} \cdot Z_{T1} + Z_{P1} \cdot Z_{T1}) \div Z_{P1}$      $Z_{ST\Delta 1} = 0.006 + 0.05j$      $Y_{ST1} = Z_{ST\Delta 1}^{-1}$

$Z_{PS\Delta 2} = (Z_{P2} \cdot Z_{S2} + Z_{S2} \cdot Z_{T2} + Z_{P2} \cdot Z_{T2}) \div Z_{T2}$      $Z_{PS\Delta 2} = 0.012 + 0.087j$      $Y_{PS2} = Z_{PS\Delta 2}^{-1}$

Convert TEE equivalent into delta equivalent via wye-delta transform & find bus admittance for T2

$Z_{PT\Delta 2} = (Z_{P2} \cdot Z_{S2} + Z_{S2} \cdot Z_{T2} + Z_{P2} \cdot Z_{T2}) \div Z_{S2}$      $Z_{PT\Delta 2} = -0.047 - 0.234j$      $Y_{PT2} = Z_{PT\Delta 2}^{-1}$

$Z_{ST\Delta 2} = (Z_{P2} \cdot Z_{S2} + Z_{S2} \cdot Z_{T2} + Z_{P2} \cdot Z_{T2}) \div Z_{P2}$      $Z_{ST\Delta 2} = 0.006 + 0.05j$      $Y_{ST2} = Z_{ST\Delta 2}^{-1}$

$Y_{PS} = Y_{PS1} + Y_{PS2}$        $Y_{PT} = Y_{PT1} + Y_{PT2}$        $Y_{ST} = Y_{ST1} + Y_{ST2}$

Calc parallel bus admittance

$V_S = 1 \cdot \text{pu}$        $V_T = 1 \cdot \text{pu}$

Standard starting point for unknown voltages

Given  $\overline{S_S} \div \overline{V_S} = -Y_{PS} \cdot V_P + (Y_{PS} + Y_{ST}) \cdot V_S - Y_{ST} \cdot V_T$

Power flow equations in standard bus admittance format

$\overline{S_T} \div \overline{V_T} = -Y_{PT} \cdot V_P - Y_{ST} \cdot V_S + (Y_{ST} + Y_{PT}) \cdot V_T$

$\begin{pmatrix} V_S \\ V_T \end{pmatrix} = \text{Find}(V_S, V_T)$      $V_S = 0.954 - 0.094j$      $V_T = 0.928 - 0.134j$

Power flow solution for S & T bus voltages

$I_S = Y_{PS} \cdot (V_P - V_S) + Y_{ST} \cdot (V_T - V_S)$      $I_T = Y_{PT} \cdot (V_P - V_T) + Y_{ST} \cdot (V_S - V_T)$      $I_P = I_S + I_T$

Calculate bus currents from converged solution

Check Solution:  $|V_S \cdot \overline{I_S}| \cdot S_{base} = 70 \text{MVA}$      $|V_T \cdot \overline{I_T}| \cdot S_{base} = 50 \text{MVA}$

Ok: Converged solution matches specified load MVAs and specified power factors

$\cos(\text{angld}(V_S \cdot \overline{I_S})) = 0.91$      $\cos(\text{angld}(V_T \cdot \overline{I_T})) = 0.89$

$S_{LoadLoss} = V_P \cdot \overline{I_P} - V_S \cdot \overline{I_S} - V_T \cdot \overline{I_T}$        $S_{LoadLoss} = 0.678 + 17.137j\%$

Loss = power in - power out

$S_{LossTotal} = S_{NoLoad} + S_{LoadLoss}$        $S_{LossTotal} = 0.801 + 18.591j\%$

Losses calculated at:

**Load Loss:**       $S_{LoadLoss} \cdot S_{base} = 677.952 + 17137.486j \text{kVA}$

$V_P \cdot V_{base} = 245 \text{kV}$

**No-Load Loss:**     $S_{NoLoad} \cdot S_{base} = 123.114 + 1453.336j \text{kVA}$

$|S_S \cdot S_{base}| = 70 \text{MVA}$

**Total Loss:**       $S_{LossTotal} \cdot S_{base} = 801.066 + 18590.822j \text{kVA}$

$|S_T \cdot S_{base}| = 50 \text{MVA}$

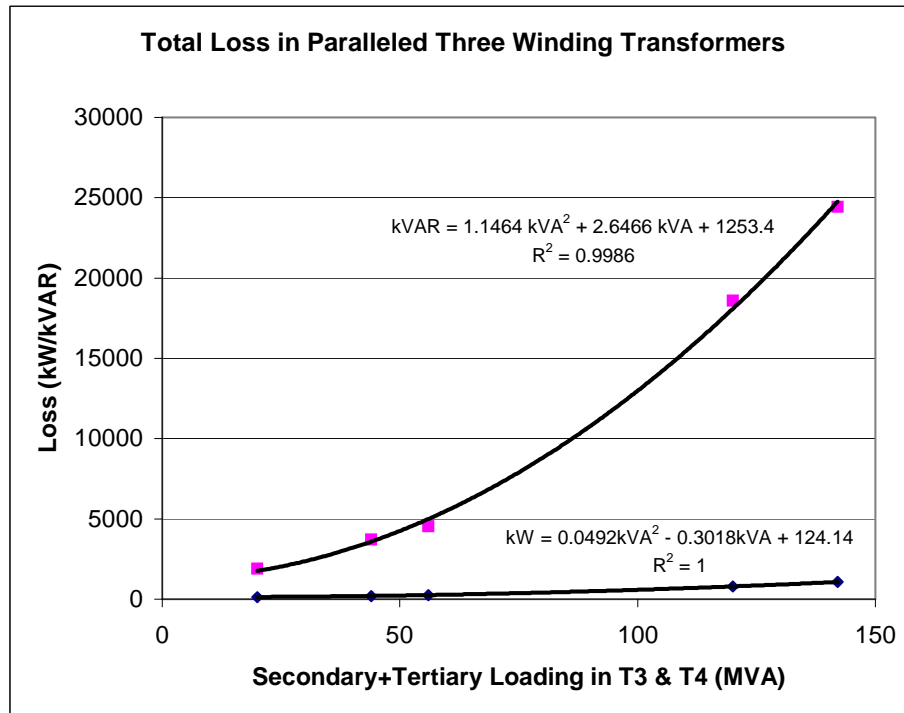
**SUMMARY TABLE OF RESULTS**

| MVA |    | PF   |      | Total Loss |            |
|-----|----|------|------|------------|------------|
| T   | S  | T    | S    | kW         | kVAR       |
| 10  | 10 | 0.85 | 0.91 | 139.677    | 1898.13j   |
| 20  | 24 | 0.97 | 0.88 | 204.187    | 3704.404j  |
| 40  | 16 | 0.92 | 0.94 | 260.152    | 4545.652j  |
| 70  | 50 | 0.91 | 0.89 | 801.066    | 18590.822j |
| 90  | 52 | 0.93 | 0.96 | 1071.375   | 24436.18j  |

Losses at other load combinations on the S & T terminals

Plotting the total loss as a function of total delivered MVA results in the figure below. The total loss for both transformers operating in parallel can be reliably estimated by summing the *meter* readings and applying the coefficients listed in the equations.

| T MVA | S MVA | Total | kW Loss  | kVAR Loss |
|-------|-------|-------|----------|-----------|
| 10    | 10    | 20    | 139.677  | 1898.13   |
| 20    | 24    | 44    | 204.187  | 3704.404  |
| 40    | 16    | 56    | 260.152  | 4545.652  |
| 70    | 50    | 120   | 801.066  | 18590.822 |
| 90    | 52    | 142   | 1071.375 | 24436.18  |



Example 4 can be expanded to accommodate any number of transformers operating in parallel by summing the equivalent delta admittances.

### C.6.1 Existing Metering Does Not Record Varhours

For the *settlement* system, Method 2 requires the *meters* to record both kWh and kVARh. Where the *meter* does not record kVARh, the *IESO* will create a summary (virtual) kVARh *meter* populated with zero readings for all intervals until the *metering installation* is replaced by compliant *meters*.

– End of Section –





## References

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| <b>Document ID</b> | <b>Document Title</b>  |
|--------------------|--|
| MDP_RUL_0002       | Market Rules   |
| MDP_STD_0005       | Site-Specific Loss Adjustments: Requirements for Adjustment of Meter Readings for Site-Specific Losses in the IESO-Administered Market |
| MDP_STD_0004       | Wholesale Revenue Metering Standard—Hardware   |
| MDP_MAN_0003       | Market Manual 3, Metering, Part 3.0: Metering Overview   |
| MDP_PRO_0013       | Market Manual 3: Metering, Part 3.2: Meter Point Registration and Maintenance  |
| IMP_PRO_0047       | Market Manual 3: Metering, Part 3.7: Totalization Table Registration   |
|                    | MV-STAR Reference Guide – Loss Equations   |

– End of Document –